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Thermo-electro-mechanical vibration of coupled piezoelectric-nanoplate systems under non-uniform voltage distribution embedded in Pasternak elastic medium

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A R T I C L E I N F O

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This article is lovingly dedicated to the memory of Akbar Javadi. He was very kind and generous.

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A B S T R A C T

In the present paper, the thermo-electro-mechanical vibration characteristics of a piezoelectric-nanoplate system (PNPS) embedded in a polymer matrix are investigated. The system is subjected to a non-uniform voltage distribution. The voltage distribution and in-plane preloads are very important in the resonance mode of smart composite nanostructures using PNPS. Small scale effects are taken into consideration using the nonlocal continuum mechanics. Hamilton's principle is employed to derive the nonlocal equations of motion. The governing equations are solved for various boundary conditions by using differential quadrature method (DQM). To verify the accuracy of the present results, a closed-form solution is also derived for the natural frequencies of simply supported PNPSs. The results of DQM are compared with those of exact solution and an excellent agreement is found. Finally, the effects of initial preload, temperature change, boundary conditions, aspect ratio, length-to-thickness ratio, nonlocal and non-uniform parameters on the vibration characteristics of PNPSs are studied. It is shown that the natural frequencies are quite sensitive to the non-uniform and nonlocal parameters.

1. Introduction

Invention of ZnO piezoelectric nanowires has opened up a new field in nanotechnology [1]. Since then, a variety of piezoelectric nanostructures such as ZnS, PZT, GaN and BaTiO have been successfully synthesized and characterized [2–5]. Primary studies showed that the mechanical properties of piezoelectric nanostructural elements such as nanowire, nanobeam, nanobelt and nanoplate were different from other well-known materials [6]. Because of the superior properties of these smart materials, they have promising applications in micro electro-mechanical systems (MEMS) and nano electro-mechanical systems (NEMS) such as field-effect transistors [7], gas sensors [8], nanogenerators [9], piezoelectric gated diodes [10], nanoresonators and nanooscillators [11]. Furthermore, recently, Lian et al. [12] synthesized mesoporous $(ZnO)_x(MgO)_{1-x}$ nanoplates from a solution containing zinc acetate and magnesium acetate by a template-free solvothermal synthetic method followed by subsequent calcination. They have shown that the $(ZnO)_x(MgO)_{1-x}$ nanoplates have high photocatalytic performance and thus are promising candidates for polluted water treatment. Due to these potential applications, understanding the vibration response of piezoelectric nanostructures under thermo-electro-mechanical loading is an important problem.

Continuum modeling of nanostructures has received a great deal of attention from research communities because controlled experiments in nanoscale are difficult and molecular dynamic simulations (MD) are highly computationally expensive, especially for the nanostructures with large numbers of atoms or molecules inside them. The use of classical continuum models may be uncertain in the analysis of nanostructures because of their size-dependent properties. In recent years, various higher order continuum theories such as couple stress theory [13], strain gradient elasticity theory [14], modified couple stress theory [15] and nonlocal elasticity theory [16,17] have been developed in order to capture size effects. Among all these modified continuum theories, the nonlocal theory of Eringen has been widely used in the theoretical investigations of small-scale structures [18–28]. Ansari et al. [29] studied the axial buckling of single-walled carbon nanotubes (SWCNTs) in thermal environments using Donnell shell theory and Rayleigh-Ritz technique. In another work, the free vibration of

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carbon nanotubes (CNTs) was analyzed based on Timoshenko beam theory and discrete singular convolution method [30]. Inspired by the development of continuum based models for CNTs, modified beam theories have been used for the determination of mechanical characteristics of microtubules (MTs). Civalek and Akgöz [31] employed nonlocal Euler–Bernoulli beam model and differential quadrature method to study the vibration response of MTs. More recently, Farajpour et al. [32] presented an explicit formula for the length-dependent persistence length of microtubules with consideration of surface effects. Further, they examined the influence of surface energy and residual surface stress on the buckling characteristics of MT networks in living cells.

The nonlocal elasticity theory is based on this assumption that the stress tensor at an arbitrary point in the domain of nanomaterial depends not only on the strain tensor at that point but also on strain tensor at all other points in the domain. Both atomistic simulation results and experimental observations on phonon dispersion have shown the accuracy of this observation [16]. Based on lattice dynamics and molecular dynamics simulations, Chen et al. [33] provided an atomic viewpoint to examine micro-continuum field theories including micro-morphic theory, micro-structure theory, micro-polar theory, Cosserat theory, nonlocal theory and couple stress theory. They reported that the nonlocal continuum model is reasonable in comparison with other modified theories. Furthermore, Ansari et al. [34] have shown that the nonlocal elasticity theory is quite accurate and reliable for the free vibration analysis of single-layered graphene sheets (SLGSs) by employing molecular dynamics simulations. In another work, Shen et al. [35] reported that the results of nonlocal plate theory with consideration of appropriate small scale coefficients are in good agreement with those of MD simulations for the nonlinear vibration of rectangular SLGSs in thermal environments.

A review of the literature shows that compared to the nanorods, carbon nanotubes and graphene sheets [18–28], few research works have been reported on the continuum based analysis of piezoelectric nanostructures, especially for the mechanical behavior taking into account the effect of elastic foundation. Based on the Euler–Bernoulli beam model, Wang and Feng [36] studied the effect of surface stresses on the vibration and buckling behaviors of piezoelectric nanowires. They considered the influence of surface stresses by applying a curvature-dependent distributed transverse loading along the nanowire. Furthermore, the influences of surface elastic modulus, residual surface stress and surface piezoelectricity on the electromechanical response of a curved piezoelectric nanobeam were investigated by the Euler–Bernoulli beam theory [37]. Gheshlaghi and Hasheminejad [38] analyzed the free vibration of piezoelectric nanowires with consideration of both surface and small scale effects. The nonlocal effects on the linear [39] and nonlinear [40] vibration characteristics of piezoelectric nanobeams were studied using the nonlocal Timoshenko beam theory. In these papers, it has been reported that an increase in the nonlocal parameter leads to both smaller linear and nonlinear frequencies but a higher nonlinear frequency ratio. An analytical approach for the buckling analysis and smart control of single-layered graphene sheets (SLGSs) using coupled polyvinylidene fluoride (PVDF) nanoplates was presented by Arani and his co-authors [41]. They found that the electric field and its direction significantly affect the magnitude of the critical buckling load. In addition, Yan and Jiang [42,43] studied the electroelastic, vibration and buckling responses of a thin piezoelectric plate with nanoscale thickness considering surface effects. In another work, Liu et al. [44] investigated the thermo-electro-mechanical free vibration of a single piezoelectric nanoplate without elastic medium based on the nonlocal elasticity and Kirchhoff plate theory. They assumed that all edges of piezoelectric nanoplate are simply supported. The size-dependent electromechanical behavior of circular nanoplates made of piezoelectric materials was also examined using the Gurtin–Murdoch theory [45].

All these research works are limited to the single piezoelectric nanostructures (e.g. nanowires, nanobeams and nanoplates). In a composite nanostructure, piezoelectric materials may be coupled to each other by bonding resins to form a complex-piezoelectric-system (CPS). A simple example of this system is made of N piezoelectric nanoscale layers which are bonded by elastic medium such as polymer matrix. The piezoelectric-nanoplate-systems (PNPSs) can be adjusted in order to meet specific nano-engineering requirements. Hence, in view of practical applications, the mechanical behavior of PNPSs is an important problem. Recently, Murmu et al. [46] and Murmu and Adhikari [47] investigated the linear buckling and vibration of bonded double-nanoplate-systems without piezoelectric properties using the nonlocal elasticity theory.

To the authors' best knowledge, up to now, the vibration of PNPSs under thermo-electro-mechanical loading is not studied in the literature. On the other hand, generally, the piezoelectric layers may be subjected to different external electric voltages. Thus, in the present paper, the transverse vibration of PNPSs embedded in a polymer matrix under non-uniform electrical loading is investigated. Using nonlocal elasticity theory and Hamilton's principle, the differential equations of motion of PNPSs are derived. The influences of normal and shear deformations of inner and outer polymer matrices are taken into consideration employing Pasternak foundation model. Differential quadrature method (DQM) is used to solve the governing equations for simply supported boundary conditions, clamped boundary conditions and various combinations of them. To verify the accuracy of the DQM solution, the equations of motion of simply supported PNPSs are also solved by Navier's method. The predicted results by DQM are successfully compared with those of the exact one. The effects of small size and elastic foundation parameters on the natural frequencies of piezoelectric-nanoplate systems through considering various parameters such as nonlocal parameter, non-uniform parameter, temperature change and aspect ratio are examined and discussed. The results show that the nonlocal and non-uniform parameters have prominent effects on the vibration behavior of the PNPS. It is anticipated that the results of the present work would be helpful for designing NEMS/MEMS components using smart composite nanostructures.

2. Mathematical modeling

In the following section, a nonlocal continuum model is developed for the vibration analysis of piezoelectric-nanoplate-systems (PNPS). A rectangular piezoelectric nanoplate (PNP) with uniform thickness (h) is shown in Fig. 1. Cartesian coordinate frame with

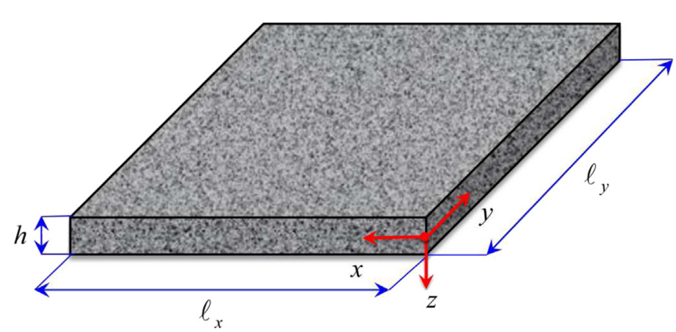

Fig. 1. A continuum model of a rectangular piezoelectric nanoplate (PNP).